Experimental Study of Liquid Fuel Spray Combustion

This PhD dissertation was carried out at the Technical University of Denmark in the Department of Mechanical Engineering and has been supervised by Associate Professor Anders Ivarsson and co-supervised by Professor Jesper Schramm. The project has been a part of the RADIATE project funded by the Danish Council for Strategic Research. Other supporters of the project have been MAN Diesel & Turbo A/S, DTU Mechanical Engineering, DTU Chemical Engineering, Sandia National Laboratories USA, Norwegian University of Science & Technology (NTNU) and University of Nottingham, Malaysia Campus. The continuing stringency of emission regulations for marine diesel engines forces a deeper understanding of the complex physical processes occurring inside the engine cylinder. A deeper understanding can lead to higher accuracy of predictive numerical models, thereby enabling evaluation of multiple engine design parameter variations which would otherwise be extremely costly and difficult to evaluate experimentally. The aim of this work is to provide a wide range of reliable experimental data of which to validate current Computational Fluid Dynamic models employing complex physics such as evaporation of atomized liquid sprays, turbulent heat and mass transport, reaction kinetics, soot formation and radiant heat transfer. These computational models are to some degree based on true physics, but simplified empirical models are unavoidable. Complex experiments are needed in order to accurately measure the specific physical quantities needed in CFD validation of these types of flames. This work is a testament to that fact. The first part of this thesis is an extensive study of optical combustion diagnostics applied to complex transient spray flames in a high temperature and pressure environment. The physiochemical properties and electromagnetic interactions in flames, of which various optical combustion diagnostics are based, have been reviewed. Key diagnostics have been presented with practical examples of their application which, together with a comprehensive review of fuel spray flames, form the motivations for the selection of diagnostics to apply in measuring key quantities in complex spray flames. In addition, the extinction imaging technique has been refined to optimize applicability in the optically harsh ambient environments into which the sprays are injected. Well defined back illumination characteristics, dimensioned according to the collection optics, remove artifacts caused by steep gradients in the refractive index while promoting high temporal resolution capabilities. The second part of this thesis consists of a comprehensive experimental campaign of fuel spray and combustion characteristics from cavitating and non-cavitating large bore injectors. The injectors have been specifically machined to isolate the effects of in-nozzle cavitation on the resulting spray and combusting characteristics. Experiments were carried out in an optically accessible constant volume combustion vessel, generating a controlled ambient environment into which the fuel sprays were injected, achieving a high degree of reproducibility. Measurements of liquid and vapor boundaries, determining key spray characteristics, were made using extinction and schlieren imaging respectively. Flame lift-off, ignition delay and soot volume fraction was measured, determining key combustion characteristics, using OH+ chemiluminescence-, natural flame luminosity- and extinction imaging respectively. The enhanced spray break-up induced by cavitation does not seem to have a radical effect when the fuel is injected into a high pressure and temperature environment. Rather, the break-up length is shortened such that the spray/jet obtains a fully developed flow closer to the nozzle, consequently shifting the flow and combustion characteristics with it. Considerations regarding the optical setup, optical elements, corrections for camera non-idealities and postprocessing methods have been developed and refined in this work to measure the optical thickness of the soot in the transient spray flames as accurately as possible. The soot cloud from these wide bore injectors was so optically thick that it appeared opaque to the camera at higher ambient temperatures. The soot volume fraction could, however, be determined in the initial formation regions up to an optical thickness of around 4, with a higher degree of certainty than prior applications of extinction imaging of soot. CFD modeled soot fields, showing good agreement with measurements, were translated to optical thickness revealing that these flames can potentially have an optical thickness up to 50 at 635 nm in the later stages of soot formation.

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